Development of an Electric Field Actuator for Thermoacoustic Instability Suppression in a Gas Turbine Combustor

Dustin Cruise, Purdue University

dcruise@purdue.edu

Abstract: Thermoacoustic instabilities are a significant challenge to implementing lean combustion in gas turbine engines. Although many theoretical control strategies have been proposed, few have been implemented due to lack of a practical control actuator. Reported in this work is the development of such an actuator, which is based on an electric field applied directly to the flame. The actuator works on the known effects of ionic wind. A laboratory burner has been constructed which exhibits a thermoacoustic instability, contains the electrodes and high-voltage amplifier for electrical forcing, and is outfitted with sensors to measure the resulting acoustic pressure. Initial testing indicates the electric field effect is great enough to modulate the acoustic pressure of the flame. The proposed solution and initial results are analyzed through a TRIZ framework to better evaluate the merits of the idea.

1. Background and Motivation

The role of the combustor in a turbine engine is to convert the stored chemical energy of the hydrocarbon fuel to mechanical work, either to drive the fan of an aero-engine for propulsion, or the electrical generator of a land-based power turbine. A practical problem with gas turbine engines is thermoacoustic instabilities.

Thermoacoustic instabilities arise from a coupling between the combustion heat release rate and chamber acoustic modes (ref). New advancements in gas turbines engines meant to increase fuel efficiency or reduce emissions [ref], have increased the likelihood of these thermoacoustic instabilities. One difficulty with instabilities is they are hard to predict during the design phase making them hard to mitigate with design changes. For this reason, active control strategies are of great research interest to the gas turbine community.

Possible control configurations investigate for active instability suppression include variable combustor geometry (ref)., pulsed fuel-injection (ref)., and plasma assisted combustion (ref). Although much research has been seen in these areas, the harsh operating conditions and stringent reliability requirements have kept the devices to the lab. Current production engines reduce the change of instability by avoiding operating conditions identified to create them during testing.

A less mature but promising method for instability suppression considered in this work is electric field actuation. As will be detailed below, flames have been shown to be manipulated by high voltage electric fields. Two likely explanations for the effect is ionic wind [ref]. and chemical kinetic enhancement [ref].

The appeal of an electric field actuator is there are no moving parts, and the available bandwidth of the actuator is greater than the instability frequencies.

2. Market Identification, Size and Growth

The gas turbine engine market consists of two segments: aero propulsion gas turbines and power generation gas turbines. The two segments have many similarities and requirements, and several models of power generation gas turbines are derivatives of aero units. For the purpose of this design study, only the aero propulsion segment shall be considered.

The International Civil Aviation Organization (ICAO) estimated the size of the 2013 world passenger air market to be 5.8 trillion passenger kilometers performed (PKP), and was expected to grow at annual rates of 6.0, 6.3, and 6.5 percent, through 2016 [Ref 1]. The second part of commercial air traffic, the air freight traffic market, was expected to grow at annual rates of 3.7,4.2, and 4.4 percent through 2016. Given these strong growth numbers and the maturity of the aviation industry, there is little market risk to the development of new technologies.

3. Value Proposition

Figure 1 shows the value canvas for the exiting jet engine (*Without Control*), the method proposed in this work (*Ionic Wind*), and a popular control approach (*Plasma*). The features metrics composing the value proposition are *Procurement Cost*, *Maintenance Cost*, *CO Emissions*, *NO_X Emissions, and Instability Amplitude*.

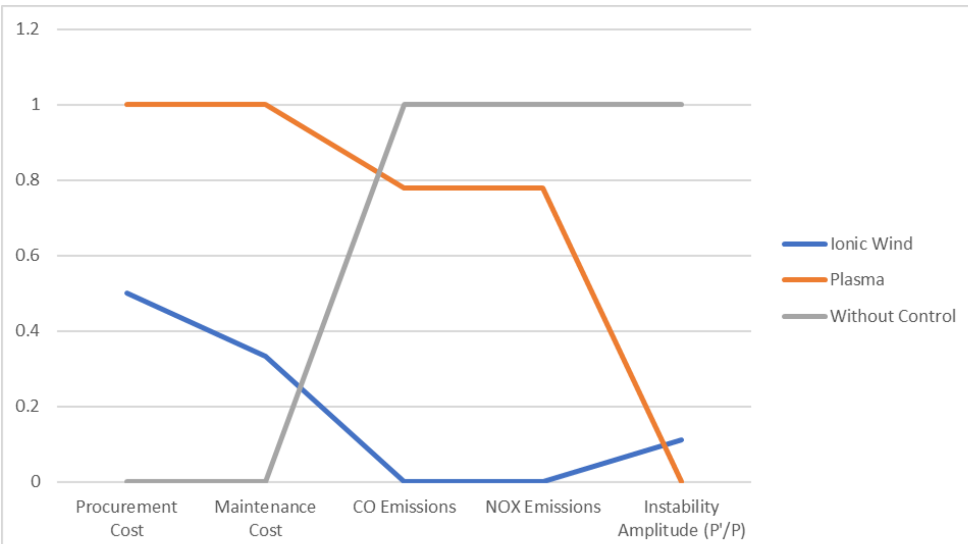

Figure 1:Value Canvas

The *Procurement Cost* represents the initial cost of the gas turbine engine. Both active control solutions would be more expensive initially, because they consist of additional components on the existing engine. It is assumed the *Plasma* method would cost more than the *Ionic Wind* solution, because the *Plasma* method operates at higher powers, which in general require greater cost to develop and stabilize.

The *Maintenance Cost* for both active control solutions would cost more than the engine without, as they add additional components which would require additional inspection and service.

The benefit of the active control solutions is seen in the emissions reduction of both CO and NO_X. The *Plasma* method is assumed to not reduce emissions as much as the *Ionic Wind* method it is a highly local effect, creating more temperature variation within the combustor, which typically leads to higher emissions.

The main function of both active control methods is to suppress the thermoacoustic instability amplitude. The *Plasma* solution has the potential of the greatest reduction here, as the *Plasma* methods have more sound power generation due to the greater ion number densities of arc discharges.

4. Cause-effect Chain

Figure 2 shows the cause-effect chain for the thermoacoustic instability problem. There are two objectives which are negatively affected by these instabilities; engine emissions output and engine damage resulting from high pressure fluctuations.

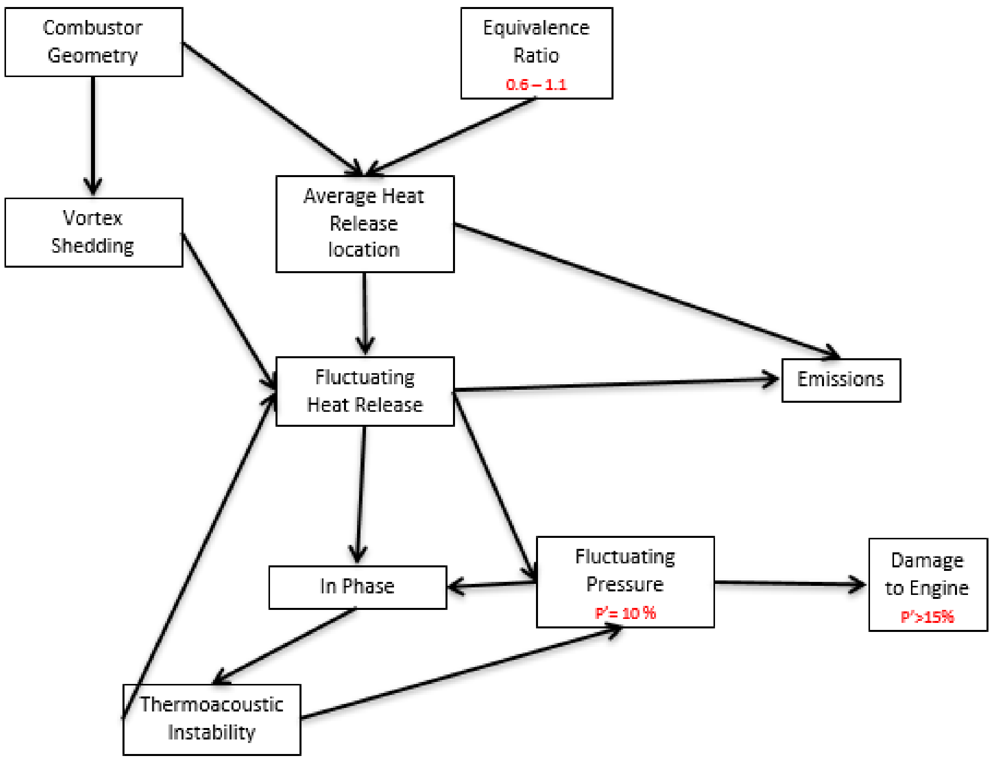

Figure 2: Cause-Effect Diagram

As the cause-effect chain shows, thermoacoustic instabilities will occur when pressure fluctuations within the combustor couple with the flame heat release fluctuations, causing both to grow. The sensitivity of the thermoacoustic instability to equivalence ratio is due to the location of heat release varying with equivalence ratio.

Starting from a lean condition which is stable, as the equivalence ratio increases, the shape of the flame and where the heat is released will change. If the new heat release occurs in an area with vortex fluctuations, the heat release rate will begin to fluctuate. This will cause a time-varying pressure fluctuation. If this frequency is close to the natural acoustic frequency of the cavity, the pressure and heat release fluctuation will be amplified and grow exponentially until reaching a limit cycle value. *Figure 3* and *Figure 4* show the recorded pressure time-series and power spectrum during an instability event.

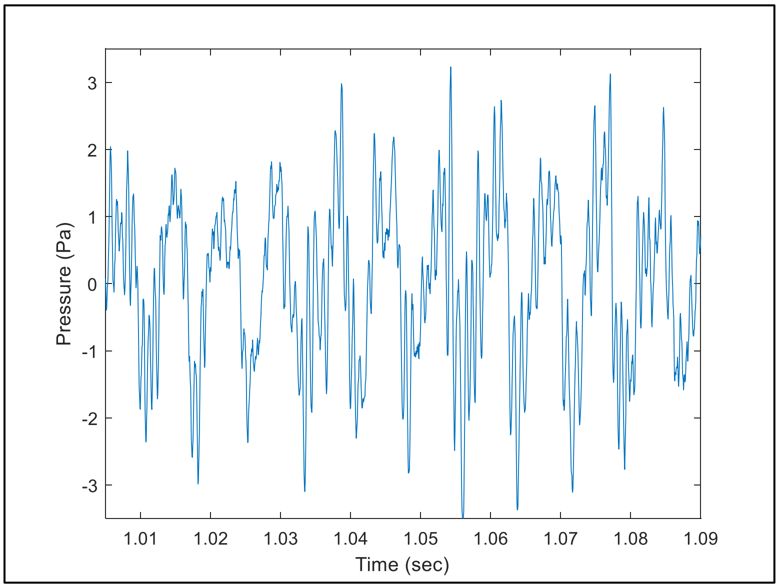

Figure 3: Typical pressure time-series during thermo-acoustic instability.

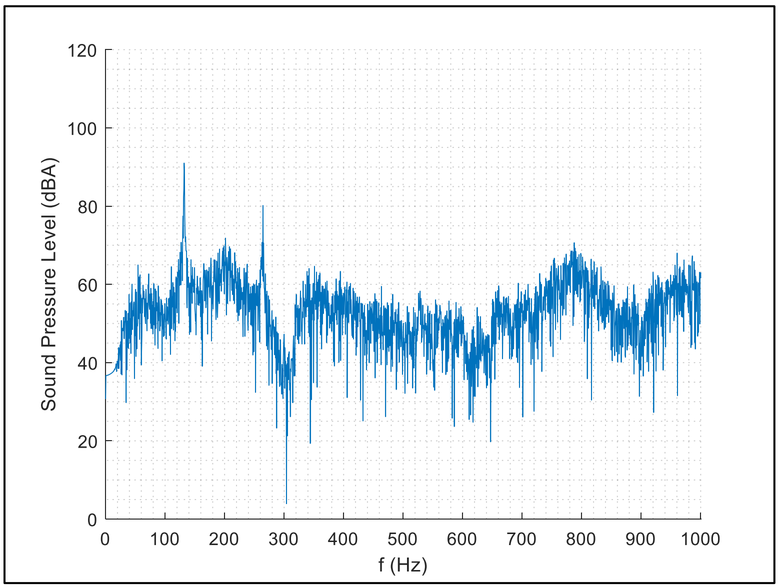

Figure 4: Power spectrum of pressure time-series during thermo-acoustic instability. Clear peaks at 132 and 264 Hz.

Figure 5 and Figure *6* show how variations in equivalence ratio effect the heat release and local temperature, and the relationship between local temperature and carbon monoxide and the various nitrous oxides emissions levels. Figure 6 shows there is a temperature range which achieve an optimal balance between the two common emissions.

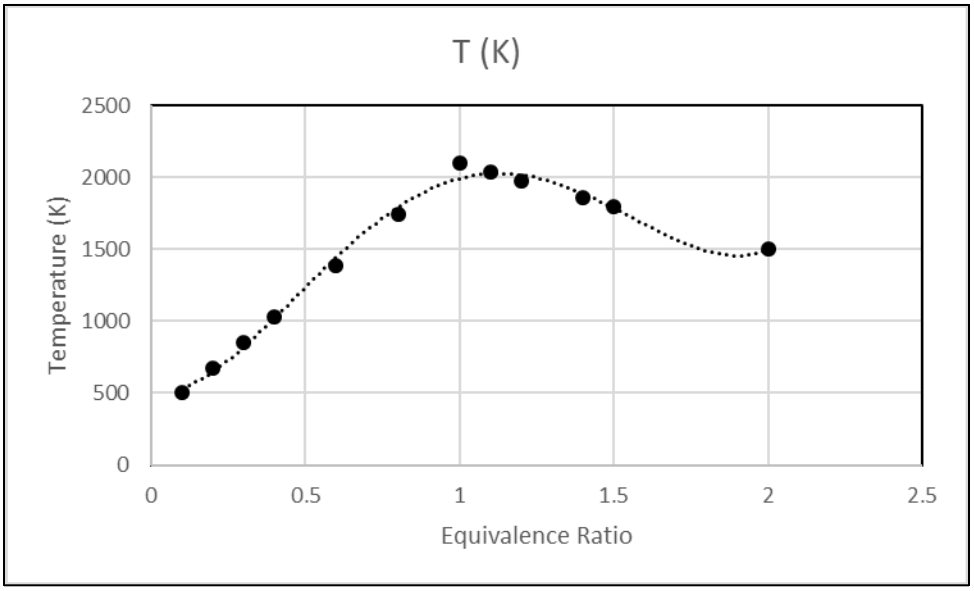

Figure 5: Adiabatic flame temperature vs. equivalence ratio for a methane-air flame.

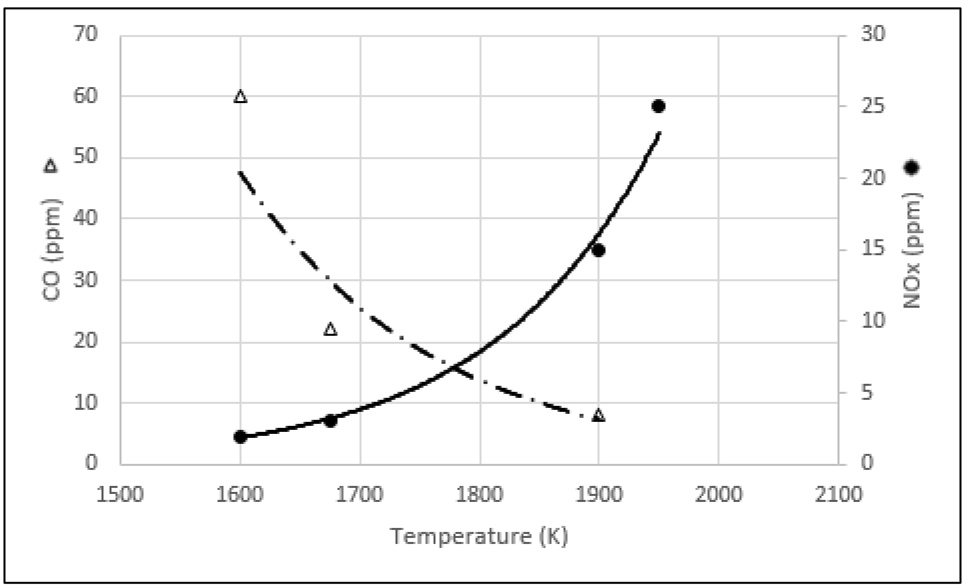

Figure 6: CO and NO_X emissions vs. flame temperature.

5. Identifying and Eliminating Trade-offs

Typical engines may have a few conditions that are prone to thermoacoustic instability. The current method for avoiding an instability is to avoid the equivalence ratios known to have them. As shown in *Table* 1, this limits the optimization of combustion performance and emissions.

Table 1: Contradictions and Solutions

Contradiction	Solution	Practicality
• Full use of equivalence ratio range for optimizing emissions • Equivalence ratio restricted due to thermoacoustic instabilities	Decouple instability from equivalence ratio with electric-field forcing. With active controller, shift unstable eigenvalues of acoustic system to stable.	High. No moving parts, minimal disruption to gas path.
• Average heat release location avoids area of vortex shedding, causing instabilities • Full flexibility of heat release location to optimize temperature profile and reduce emissions		
• High damping in acoustic cavity to avoid under-damped pressure oscillations • Little to no physical elements in combustion zone to avoid high wear items and hot spots.		

6. Problem Optimization via Ionic Wind Actuator

A key parameter for the instability to occur is the phase relationship between the pressure and heat release. The actuator developed here acts to modify the phase to cause destructive interfere, resulting in the reduction of all oscillations. A schematic of the actuator is shown in Figure 7.

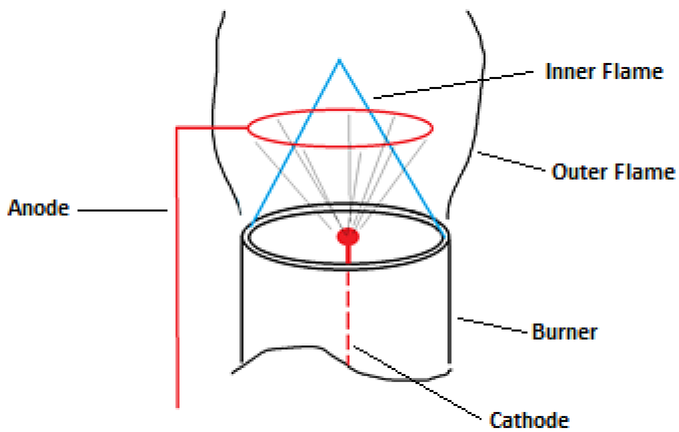

Figure 7: Schematic of flame with electrodes attached.

The actuator works based on the principal of ionic wind. A flame is a weak plasma composed of charged particles and neutral species. When an electric field is applied, the charged particles are attracted through the Coulomb force to the electrode of opposite charge. The flame in primarily composed of positive ions and electrons. The positive ions have a mass several thousand times greater than the electrons, and a much larger cross section. The ions therefore transfer more momentum to the gas than the electrons, resulting in a net fluid direction, or an "ionic wind".

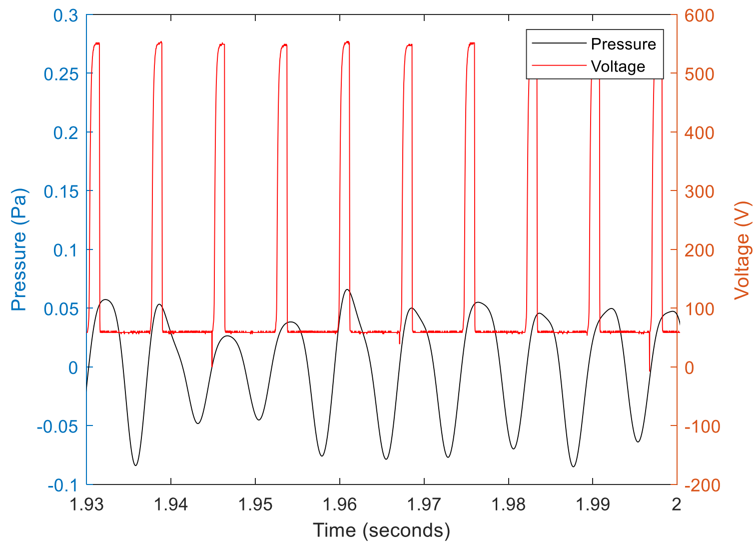

Figure 8: Voltage and pressure time-series achieved during forcing by electric field.

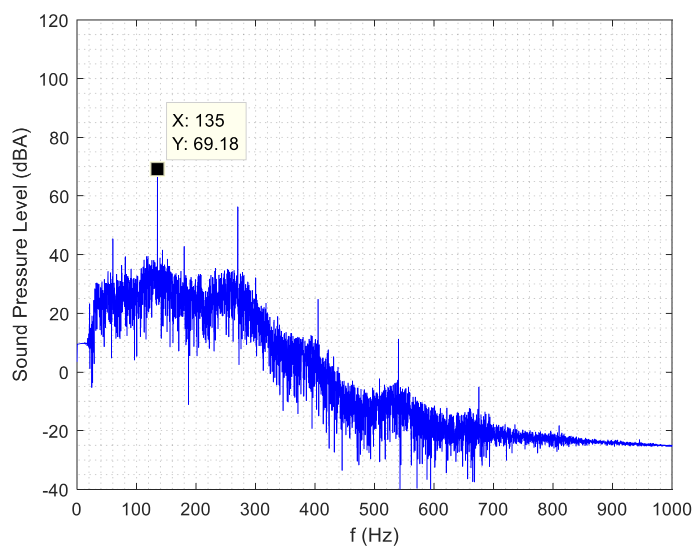

Figure 9: Power spectrum of pressure time-series during forcing by electric field. A peak amplitude of 69 dB was achieved, giving a measure of the strength of the actuator.

Initial testing of the electric field forcing ability has been promising. Figure 8 shows the collected time-series of the applied voltage and resulting pressure signal during forcing with the electric field. The power spectrum of Figure 9 shows a peak power of 69 dBa.

Although this is quite lower than the instability acoustic power of 91 dBa, the forced response testing was done without the benefit of an acoustic cavity around the flame, and therefore there was no constructive interference of the pressure wave. This cavity was left off to avoid a thermoacoustic instability during the forced response testing.

7. Remaining Work

With a proof of concept of the ionic wind actuator demonstrated, what remains is an increase in the strength of the effect, and the actuator to be used in a control loop for instability suppression.

Due to the cavity amplifying both the effect of the instability and the forced response, it is difficult to estimate the amplification amount in order to compare the 69 dBa forced amplitude without cavity, with the 91 dBa instability amplitude with cavity. Instead of trying to isolate the effects, the actuator will next be used on the unstable system. Using the feedback controller, the phase relation of the applied voltage relative to the pressure feedback signal can be swept, and the impact of the ionic wind actuator assessed.

8. Conclusion

In this work, the mechanism of a thermoacoustic instability was analyzed using common TRIZ methods, such as cause-effect chains and function diagrams. From analyzing the components leading to an instability, a possible solution to suppressing the instability was found. Initial experimental results of the new ionic wind actuator are promising, and warrant future development and continued analysis through the TRIZ framework.

References

[1] https://www.icao.int/sustainability/pages/eap_fp_forecastmed.aspx